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A New Nearby Candidate Star Cluster in Ophiuchus at d $\simeq$ 170 pc

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ABSTRACT

The recent discoveries of nearby star clusters and associations within a few hundred pc of the Sun, as well as the order of magnitude difference in the formation rates of the embedded and open cluster populations, suggests that additional poor stellar groups are likely to be found at surprisingly close distances to the Sun. Here I describe a new nearby stellar aggregate found by virtue of the parallel proper motions, similar trigonometric parallaxes, and consistent color-magnitude distribution of its early-type members. The 120 Myr-old group lies in Ophiuchus at $d \simeq 170$ pc, with its most massive member being the 4th-magnitude post-MS B8II-III star μ Oph. The group may have escaped previous notice due to its non-negligible extinction ($A_V \simeq 0.9$ mag). If the group was born with a normal initial mass function, and the nine B- and A-type systems represent a complete system of intermediate-mass stars, then the original population was probably of order $\sim$200 systems. The age and space motion of the new cluster are very similar to those of the Pleiades, α Per cluster, and AB Dor Moving Group, suggesting that these aggregates may have formed in the same star-forming complex some $\sim 10^8$ yr ago.

Subject headings: open clusters and associations

1. Motivation

This is the first in a series of papers regarding the identification and characterization of groups of young stars within a few hundred pc of the Sun (mostly, newly discovered groups

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of young stars). The second paper (Mamajek, in prep.) will detail the identification of a new ∼20-Myr-old group within 100 pc. In this contribution, I discuss a new candidate group situated 170 pc away in Ophiuchus that appears to be similar in age to the Pleiades (≈120 Myr).

Very young stars with ages of $\lesssim$3 Myr are usually found in embedded clusters (ECs) with tens to hundreds of members, and associated with dark molecular clouds (e.g. Lada & Lada 2003; Porras et al. 2003). The vast majority of embedded clusters must not remain as bound structures identifiable as open clusters (OCs) after their molecular gas is removed. This can be inferred by estimating the formation rates of the local samples of ECs and OCs within 1 kpc of the Sun. In comparing the number of ECs to OCs within the same representative volume, and assuming a constant cluster-formation rate, Lada & Lada (2003) calculate that $\lesssim$4-7% of embedded star clusters probably survive to the age of the Pleiades (≈130 Myr). Counting only those ECs with $\gtrsim$35 members from the catalogs of Lada & Lada (2003) and Porras et al. (2003) within 1 kpc of the Sun, the local surface density of ECs in the Galactic disk appears to be ∼9 kpc^{-2}. The number of ECs with 10-35 members is roughly equal to the number of ECs with >35 members (Porras et al. 2003), so the surface density is doubled if one counts groups with >10 members. Assuming a flat cluster-formation rate, and a mean EC age of ∼2 Myr, Lada & Lada (2003) estimate for their sample of local ECs with >35 members a formation rate of ∼4 Myr^{-1} kpc^{-2}. If one assumes that the census of OCs with ages of 10-100 Myr and $d \leq 1$ kpc is complete (using the 2006 update[1] of the catalog of Dias et al. 2002), then the local density of such OCs is ∼35 kpc^{-2}, and the OC formation rate is ∼0.34 Myr^{-1} kpc^{-2} (similar to previous estimates by Elmegreen & Clemens (1985) and Battinelli & Capuzzo-Dolcetta (1991)). The actual cluster formation rate may be somewhat higher as nearby clusters are still being discovered (Platais et al. 1998; Mamajek et al. 1999; Alessi et al. 2003; Kharchenko et al. 2005). These calculations suggest that only ∼9% of the ECs seen today would be hypothetically identified as OCs ∼10-100 Myr in the future, and that ∼90% of ECs likely evolve into unbound structures that might be identifiable as "associations" or "moving groups". Another conclusion is that for every cataloged OC in the Sun's vicinity with age <100 Myr, there may be an *order of magnitude* more stellar aggregates with >35 members that are *not* cataloged as OCs, and there are likely to be approximately *double* that number again if one tracks the evolution of ECs with >10 members. So where are these fossil remnants of ECs that are predicted to be in copious supply?

The nearest unbound remnants of ECs that contain any O-type stars, and/or significant numbers of B-type stars, have probably been identified as OB associations (OBAs), at least

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up until ages of few$\times$10 Myr (Briceño et al. 2006). The progenitors of OBAs were probably giant molecular cloud complexes containing ensembles of ECs (with the evolutionary descendants of the individual ECs appearing later as "subgroups" in the OBAs). The OB associations within 1 kpc cataloged by de Zeeuw et al. (1999) contain between 6 and 85 B-type stars ($\overline{n_B} \simeq 45$). Young stellar groups with ages of $\sim$3-100 Myr that contain few, if any, B-type stars have only recently been identified. Given a standard initial mass function (IMF), one naively expects that for each B-type star formed, an EC will also typically produce $\sim$1 A-star, $\sim$1 F-star, $\sim$1.5 G-stars, $\sim$4 K-stars, and $\sim$28 M-stars (where I have adopted the IMF of Kroupa 2001, and the spectral types are reflective of the resultant main sequence population). Hence, if born with a Kroupa (2001) IMF, an unrecognized cluster or association with $\sim$5 B-type stars may have represented an embedded cluster of $\sim$200 stars. That such small groups can escape detection is well illustrated by that fact that at least 5 well-studied stellar aggregates with ages of $\lesssim$30 Myr and distances of $\lesssim$110 pc have been discovered over the past decade (e.g. η Cha, ϵ Cha, TW Hya, β Pic, Tuc-Hor groups; Mamajek et al. 1999, 2000; Feigelson et al. 2003; Kastner et al. 1997; Barrado y Navascués et al. 1999; Zuckerman & Webb 2000; Torres et al. 2000). Each contains between zero (TW Hya Assn.) and four (Tuc-Hor) B-type stars, tens of low-mass stars, and no molecular gas (except for ϵ Cha, the youngest of these). Lacking bright, hot stars from their ranks, the discovery of these groups had to await the era of large uniform astrometric databases with accurate proper motions and trigonometric parallaxes (i.e. *Hipparcos*; Perryman & ESA 1997) and an X-ray all-sky survey (i.e. *ROSAT*; Voges et al. 1999). Any heretofore missing groups may be identifiable by virtue of their common proper motions and distances (where the higher mass stars will be preferentially conspicuous due to the shallow magnitude limits of contemporary astrometric catalogs). The low-mass members of such groups may be identifiable by virtue of various youth signatures, with strong X-ray emission being the most conspicuous. The most unbound aggregates may even lack a distinguishable nucleus (e.g. TW Hya association), and may simply be identifiable as a slight over-density of young stars of similar age and space motion.

2. Analysis

In an effort to further investigate the memberships and kinematics of known young, nearby stellar associations, as well as identify new ones, the author has compiled an extensive list of astrometric data for a sample of plausibly young stars within a few hundred pc of the Sun. This list includes OBA-type stars from the compiled ASCC astrometric catalog (Kharchenko 2001), *ROSAT* All-Sky Survey X-ray sources (RASS; Voges et al. 1999, 2000) with optical counterparts in the Tycho-2 (Høg et al. 2000) or UCAC2 (Zacharias et al. 2004) catalogs, and previously identified pre-MS stars (Ducourant et al. 2005; Herbig & Bell 1988). For constructing the RASS/Tycho-2/UCAC2 catalog, an optimal X-ray/optical separation of 40" was adopted (Neuhaeuser et al. 1995). This compilation of catalogs provides critical astrometric and X-ray data for characterizing the membership and kinematics of nearby, young stellar groups, as well as identifying new ones.

The Ophiuchus region is rich in recent, and on-going, star-formation at $d \simeq 140$ pc (e.g. LDN 1688, Upper Sco subgroup of Sco-Cen OB association, etc.; Blaauw 1991; de Zeeuw et al. 1999; Preibisch & Mamajek 2006). In plotting the positions and proper motion vectors for young stars over several thousand square degrees in the general direction of the Oph-Sco-Cen star-formation region, I noticed a previously unrecognized, tight group of early-type stars with nearly parallel proper motions in Ophiuchus ($\mu_{\alpha*}$, $\mu_\delta \simeq$ –11.5, –20.5 mas yr^{-1}; Fig. 1). The densest concentration of stars in this group is roughly centered on μ Oph (B8II-III; Houk & Swift 1999), which appears to be the brightest member of the group (V = 4.58^m; Perryman & ESA 1997). Several early-type stars with ASCC proper motions nearly identical to that of μ Oph can be found to the south and west of the μ Oph clump, but no obvious additional early-type candidate members to the north and east were found. Four early-type stars within a ∼20' diameter region near (α, δ = 264°.5, –8°.1; 17^{h}38^m –8°6'; J2000) comprise what appears to be the "nucleus" of this group: μ Oph (HD 159975), HD 159874 (B8IV/V; V = 7.83^m), HD 160038 (B9V; V = 7.98^m), and HD 160037 (A0V; V = 8.90^m; Houk & Swift 1999; Perryman & ESA 1997). The projected separations between these four stars (at an assumed distance of 173 pc; §2.3) are 0.1-0.7 pc, which are larger than the maximum observed separations for binary stars with late B-type primaries (∼0.1 pc; e.g. Abt 1988). A Digitized Sky Survey image of the nucleus region is shown in Fig. 2, and the nucleus stars are indexed 1-4 in order of brightness at V band.

2.1. Selection

I assembled a preliminary sample of candidate members by selecting those early-type stars with ASCC proper motions within 3 mas yr^{-1} of ($\mu_{\alpha*}$, μ_δ) = (–11.5, –20.5 mas yr^{-1}), and with positions within a 7° box centered on (α, δ = 263°.8, –9°.0; J2000). The motivation for using these particular selection values is empirical, based on the conspicuous presence of the "nucleus" in position and proper motion space (Figs. 1 & 2), and the clean detachment of the group from other stars in proper motion space. Note that for an assumed distance of 173 pc (see §2.3), 1 mas yr^{-1} translates into 0.8 km s^{-1}.

The astrometric data for these stars are provided in Table 1, and the photometric data and spectral types are presented in Table 2. The points on the color-magnitude diagram for these objects are roughly consistent with constituting a reddened, co-distant population (discussed further in §2.4). The hypothesis that this is a stellar association of some kind seems to be tenable, so we proceed to solve for the reddening, age, and distance of the system.

2.2. Reddening

There are two good reasons for investigating the reddening of the μ Oph group candidate members in more detail: (1) one needs to account for reddening in order to estimate the intrinsic brightnesses of the stars; critical to estimating the isochronal age of the aggregate, and (2) there are reports in the literature of anomalous reddening in the general direction of Oph and Sco (Whittet & van Breda 1980; Turner 1989), in which case the standard ratio of total to selective extinction ($R_V = A_V/E_{B-V}$) might not be close to the (commonly assumed) Galactic mean value of $R \simeq 3.1$ (Mathis 1990). Using the photometry and spectral type data in Table 2, and eqn. 39 and the 2MASS and Johnson filter data from Fiorucci & Munari (2003, for the regime of hot stars with low reddening), I estimated R_V via three derived equations:

$$R_V = 1.69\frac{E(V-J)}{E(B-V)} - 0.66 \tag{1}$$

$$R_V = 1.35\frac{E(V-H)}{E(B-V)} - 0.34 \tag{2}$$

$$R_V = 1.20\frac{E(V-K_s)}{E(B-V)} - 0.18 \tag{3}$$

For a given star, the three R_V values are not independent estimates, as they all depend on the same B and V photometry. For this reason, I quote in Table 2 the mean R_V values and adopt their standard deviation (rather than the standard error) as an estimate of the uncertainty in R_V. An additional (negligible) uncertainty of ±0.1 in R_V was included to take into account the uncertainty in the spectral types (assumed to be accurate to ±1 subtype). The typical uncertainty in R_V for a given star was then ±0.2. The unweighted mean R_V value among the candidate members is $\overline{R_V} = 3.53 \pm 0.16$ ($\sigma = 0.45$), after excluding star #9 (HD 158875; $R_V = 6.1$), which fails Chauvenet's criterion and can be considered a statistical outlier (Bevington & Robinson 1992). As the 2MASS photometry for μ Oph itself was of poor quality, no useful estimate of R_V could be calculated, so I adopt the mean group value for this star. That the dispersion in R_V values is larger than the observational uncertainties suggests that it is more appropriate to adopt the individual R_V values in Table 2 for calculating extinctions, rather than adopting a mean group value. The mean R_V (3.5) is intermediate between the Galactic mean value (3.1) and that reported for the Sco-Oph region by Whittet & van Breda (1980, $R_V = 3.9$). The $B-V$ color excesses for the nine stars in Table 2 range from $E_{B-V} = 0.19$ to 0.31, and are consistent with a mean value of $\overline{E_{B-V}} = 0.26 \pm 0.02$ ($\sigma = 0.05$ mag). The mean V band extinction for the B- and A-type stars is then $\overline{A_V} \simeq \overline{R_V} \times \overline{E_{B-V}} = 0.9 \pm 0.1$ mag.

2.3. Distance

The *Hipparcos* and Tycho parallaxes for the 9 group members in Table 1 are statistically consistent with one another, within their published uncertainties. The inverse-variance-weighted mean trigonometric parallax for the sample is $\overline{\varpi} = 5.77 \pm 0.48$ mas, which translates to a distance of 173^{+16}_{-13} pc. For the 6 stars with accurate *Hipparcos* parallaxes, comparing the individual parallaxes to the weighted mean value (5.77 mas) using a χ^2 test gives $\chi^2/\nu = 1.85/5$ for a high χ^2 probability of 87%. For the full sample of *Hipparcos* and Tycho parallax measurements (15 values), comparing the individual parallaxes to the weighted mean value using a χ^2 test gives $\chi^2/\nu = 11.7/14$, and a χ^2 probability of 63%. The former is the more demanding test, and suggests that the individual parallax measurements (when available) are very consistent with the mean value. The later test is less enlightening, as the the Tycho parallax errors are typically large (∼10 mas), and most B- and A-type field stars will have actual parallaxes of ∼1-15 mas anyway, due to the magnitude limit of the Tycho catalog. An upper limit on the dispersion of distances will be presented in §3.4. Throughout the rest of this paper, I adopt a group distance of 173^{+16}_{-13} pc.

2.4. Age

With the reddening and distance towards the sample quantified, one can attempt to estimate an isochronal age for the system. For this purpose, I employ the evolutionary tracks and isochrones from Lejeune & Schaerer (2001) for metal mass fractions of $Z = 0.008$ and 0.020. The dereddened color vs. absolute magnitude diagram for the candidate cluster sample is shown in Fig. 3. The metal fractions of the two sets of isochrones bracket the range of recent estimates of the solar Z ($0.0126 < Z_{\odot} < 0.0189$; e.g. Anders & Grevesse 1989; Grevesse & Sauval 1998; Lodders 2003; Asplund et al. 2004; Antia & Basu 2006). The assumption of solar Z should be an excellent first assumption, as the local open cluster population has a mean metallicity consistent with solar, with only a ±0.1 dex dispersion in [Fe/H] (Twarog et al. 1997). For the solar metal fraction ($Z \simeq 0.015$), the isochronal age of the post-MS star μ Oph is log(age/yr) $= 8.08 \pm 0.05$, and nearly independent of Z over the range probed. The main sequence stars are consistent (within their errors) of lying on this isochrone for solar metallicity ($Z \simeq 0.015$) at the mean *Hipparcos*-Tycho distance (173 pc). The turn-off age estimate unfortunately hinges sensitively on the placement of the post-MS (H shell-burning) star μ Oph, but Fig. 3 suggests that the color-magnitude-distance data for this kinematic group are consistent with a coeval and co-distant cluster.

To test whether the age estimate for the μ Oph group is consistent with that for other well-studied clusters, I estimated ages for the α Per and Pleiades clusters using *Hipparcos* photometry of evolved MS and post-MS stars. I adopt the distance and reddening for the α Per cluster, as well as the reddening for the Pleiades, from Pinsonneault et al. (1998), and use the recent Pleiades distance estimate from Soderblom et al. (2005). Using the median dereddened CMD position for the cluster members with $V < 6^m$ from de Zeeuw et al. (1999), I estimate a turnoff age of 95 Myr for the α Per cluster. Using the same technique on a sample of high mass stars in the Pleiades ($V < 5^m$ members from Robichon et al. 1999) yields an age of 130 Myr. These turn off age estimates are in excellent agreement (~5%) with the most recent Li-depletion boundary (LDB) ages of 85 ± 10 Myr (α Per) and 130 ± 20 Myr (Pleiades; Barrado y Navascués et al. 2004). Given the statistical uncertainty in the isochronal age for μ Oph (12%), the cross-calibration error between the LDB and turnoff ages for the benchmark α Per and Pleiades clusters (~5%), and the published uncertainties in the LDB ages (here assumed to be errors in the absolute ages; ≈10-15%; Barrado y Navascués et al. 2004), I conservatively estimate the uncertainty in the age of the new cluster to be ≈20%. The age of the group is then 120 ± 25 Myr.

2.5. Space Motion

The bulk space motion of the cluster is an interesting quantity to compare to other nearby young stellar groups, and requires accurate estimates of the group's distance, radial velocity, and proper motion. The distance to the group (173^{+16}_{-13} pc) was determined earlier (§2.3), and appears to be well-constrained. Unfortunately, at present, only two members of the new cluster have radial velocity measurements, but they are consistent: μ Oph (–18.5 $\pm$ 1.4 km s^{-1}; Barbier-Brossat & Figon 2000) and HD 158450 (–22.0 $\pm$ 4.2 km s^{-1}; Grenier et al. 1999). The weighted mean radial velocity for these two stars is -18.9 ± 1.3 km s^{-1}. Using the best available proper motions for the nine stars (Tycho-2 for μ Oph, and UCAC2 for the remaining eight), I estimate a mean proper motion of $\overline{\mu_{\alpha*}} = -12.1 \pm 0.4$ mas yr^{-1}, and $\overline{\mu_\delta} =$

–20.6 ± 0.4 $\mathrm{mas\,yr^{-1}}$. From these mean proper motion, radial velocity, and distance values, I estimate the barycentric space motion of the group to be (U, V, W = –12, –24, –4 $\mathrm{km\,s^{-1}}$), with ±1 $\mathrm{km\,s^{-1}}$ errors in each component. The space motion differs significantly from that of components of the local star-forming complex (the "Gould Belt"; $\lesssim$60 Myr; $U, V, W \simeq$ –10, –14, –7 $\mathrm{km\,s^{-1}}$; e.g. Sco-Cen, Ori OB1, etc.; Torra et al. 2000). Despite its spatial proximity to Sco-Cen, the age and velocity of the new group are completely inconsistent with it being a subgroup of the nearest OB association. The new group is, however, surprisingly close in both age *and* velocity to the 85 Myr-old α Per cluster (U, V, W = –15, –26, –8 $\mathrm{km\,s^{-1}}$; Robichon et al. 1999), 130 Myr-old Pleiades cluster (U, V, W = –7, –28, –15 $\mathrm{km\,s^{-1}}$) and 75-150 Myr-old AB Dor moving group (U, V, W = –8, –26, –14 $\mathrm{km\,s^{-1}}$; Luhman et al. 2005). The μ Oph group and the three later groups all lie within a few $\mathrm{km\,s^{-1}}$ of the "Pleiades branch" velocity-space feature described by Skuljan et al. (1999). These clusters also share an over-density in velocity-age space with early-type field stars ("Group B4") in the solar neighborhood with ages of $\sim$150 ± 50 Myr and mean velocity of (U, V, W = –9±5, –26±3, –9±5 $\mathrm{km\,s^{-1}}$; Asiain et al. 1999). Ostensibly, the "B4" group and the AB Dor Moving Group may be the same entity (save the slight physical clustering of young low-mass stars associated with AB Dor itself). Given the similarities in both age and space motion between the μ Oph, Pleiades, and α Per clusters, and the AB Dor and/or "B4" moving groups, it is conceivable that the newly identified cluster formed in the same star-forming complex that spawned these other well-known groups.

The properties of the new stellar aggregate are summarized in Table 3.

3. Discussion

3.1. Solar Reflex Motion?

Could this aggregate be composed of unrelated B- and A-type field stars whose projected positions are clustered in the sky, but simply demonstrating solar reflex motion? While solar reflex motion is imparted on the observed proper motion of every star, the effect can not be responsible for the nearly identical proper motions of the eight early-type stars in the proposed aggregate. The spread in proper motions is an order of magnitude smaller than that expected for an ensemble of young *field* stars (even if situated at identical distances).

Suppose that the group is actually composed of field stars at similar distances (170 pc) but with a distribution of 3D space motions representative of B- and early A-type field stars. Here I simulate the proper motions of early-type field stars using the velocity dispersion tensor for stars with $(B-V) \in$ [-0.238, 0.139] from Table 1 of Dehnen & Binney (1998), using a simple Monte Carlo technique previously employed by the author in Siegler et al. (2003). For the simulated data sets, I adopt the solar peculiar motion with respect to the LSR from Dehnen & Binney (1998). I create a Monte Carlo sample of 10^4 stars with UVW vectors drawn from the Dehnen & Binney (1998) velocity dispersion tensor, then assume that these stars lie at the distance and celestial position of the center of the μ Oph aggregate, and calculate what distribution of proper motions one would see. The simulated proper motions are consistent with $\mu_{\alpha *} = +3 \pm 8$ (1σ) mas yr^{-1} and $\mu_\delta = -5 \pm 13$ (1σ) mas yr^{-1}. The predicted scatter in proper motion components ($\sigma_\mu \simeq$ 8–13 mas yr^{-1}) is roughly an order of magnitude larger than the observed dispersion in the proper motion components for the proposed cluster ($\sim$1 mas yr^{-1}), even before accounting for the individual proper motion errors (mean errors $\sigma_\mu \simeq 1.0$ mas yr^{-1}; Table 1). The amount of *intrinsic* velocity dispersion (unaccounted for by the observational errors) is unresolvable (§3.2) – the proper motion errors appear to account for all of the observed spread. The mean proper motion of the proposed cluster is also not near the predicted proper motion locus for the field population (which is within $\sim$10 mas yr^{-1} of zero motion). From these calculations, one can rule out solar reflex motion alone as the agent for the clumping of the proper motions observed in Figs. 1.

3.2. Dynamics

How has the rather poor stellar nucleus of the μ Oph cluster survived to an age of $\sim 10^8$ years? The answer likely lies with the high density of the nucleus. For the fiducial isochrone ($Z = 0.015$; 120 Myr), the absolute magnitudes of the nucleus stars suggest masses for the nucleus stars of 5.2 $M_\odot$ (μ Oph), 3.0 $M_\odot$ (HD 159874), 2.8 $M_\odot$ (HD 160038), and 2.1 $M_\odot$ (HD 160037). The deprojected half-mass radius (Spitzer 1987) for the observed membership is approximately 0.4 pc (corresponding closely to the observed nucleus radius) and within this radius the stellar density is at least $\simeq$49 $M_\odot$ pc^{-3} (600$\times$ the local Galactic disk density of $\sim$0.08 $M_\odot$ pc^{-3}; Creze et al. 1998). This density is similar to that within a similar size volume of the η Cha cluster ($\simeq$56 $M_\odot$ pc^{-3}; calculated from Table 2 and Fig. 7 of Lyo et al. 2004). Using the formula of King (1962) and the Oort constants from Feast & Catchpole (1997), I estimate the cluster tidal radius (r_t) for the observed membership to be $\approx$4 pc.

Ideally one would like an estimate of the velocity dispersion to give some indication of the dynamical state of the group (i.e. is it bound?). If the group were bound and conformed to a Plummer model, then given the total mass (24 $M_\odot$) and half-mass radius (0.4 pc), the central 1D velocity dispersion should be $\sim$0.25 km s^{-1} (Gunn et al. 1988). This is negligible compared to the proper motion uncertainties, but consistent with the lack of a detectable spread in the tangential motions. To test to see whether an intrinsic velocity dispersion was present, I use the best long-baseline proper motions available for each star (Tycho-2 for μ Oph, and 2UCAC for the other seven stars; Table 1). The velocity dispersion can be estimated by the distribution of proper motions in the τ (tangential) direction, i.e. in the direction perpendicular to the great circle joining the position of each star and the convergent point for the group (e.g. Mamajek 2005, and references therein). The group convergent point can be estimated from the space motion vector ($\alpha_{cvp}, \delta_{cvp}$ = 108°.9, –30°.7; uncertainty of ±2°.7)[2]. The mean proper motion of the eight stars towards the convergent point is $\overline{\mu_\upsilon}$ = 23.9 mas yr^{-1} (with 1σ dispersion of 1.2 mas yr^{-1}), and the mean proper motion in the perpendicular direction is $\overline{\mu_\tau}$ = 0.0 mas yr^{-1} (with 1σ dispersion of 0.9 mas yr^{-1}). The mean uncertainties in the α and δ proper motion components are both 1.0 mas yr^{-1}, so the uncertainties in the rotated components (σ_{μ_υ} and σ_{μ_τ}) are similarly 1.0 mas yr^{-1}. Given the observational proper motion uncertainties (1.0 mas yr^{-1}), the dispersion in μ_τ (0.9 mas yr^{-1}) for these nine stars is statistically consistent with parallel motion with negligible (indeed *zero*) velocity dispersion. For reference, a tangential velocity of 1 km s^{-1} (typical for the velocity dispersion observed in OB association subgroups; Briceño et al. 2006) at d = 173 pc is equivalent to a proper motion of 1.2 mas yr^{-1}. A 1D velocity dispersion of 1 km s^{-1} added in quadrature to the proper motion uncertainties would have resulted in an observed proper motion dispersion of 1.6 mas yr^{-1}, however this is easily ruled out. Hence the data are consistent with the idea that the velocity dispersion is negligible, but a value can not be derived from modern astrometric data.

The evaporation time of the nucleus can be calculated following Binney & Tremaine (1987) for two extreme cases. In the first case, where we are dealing with a "cluster remnant" with only the four high mass stars in the nucleus, the evaporation time is short (~10^8 yr). This is perhaps not so surprisingly similar to the *isochronal* age, given the "poor" appearance of the nucleus. In the other extreme case, one posits that the four high-mass stars in the nucleus represent a complete census of 2-5.5 $M_\odot$ members, and hypothesize that there is an as-yet undetected entourage of low-mass members with masses drawn from a Kroupa (2001) initial mass function. In this case, the existence of 4 high-mass members implies that ~130 ± 60 low-stars might exist[3], for a total nucleus mass of ~60 $M_\odot$. In this case

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[2]The classic convergent point technique does not work well for stellar groups that are close together, like the μ Oph group. The convergent point algorithm described in Mamajek (2005) yields a group convergent point of $\alpha_{cvp}, \delta_{cvp} \simeq 117^\circ(^{+81^\circ}_{-19^\circ})$, $-39^\circ(^{+24^\circ}_{-15^\circ})$; (68% confidence intervals), within a long narrow (≈1°.5 wide) error ellipse oriented NW-SE. This convergent point is within 10° of the convergent point estimated from the space motion, which is pleasing (and perhaps surprising) considering the size of the error ellipse.

[3]If the nine B- and A-type stars represent a complete census of the 1.5-5.5 $M_\odot$ population that initially formed, then assuming a Kroupa (2001) IMF, the initial population may have been ~200 systems. This is

the evaporation time is of order $\sim$400 Myr. Reality probably lies in between these two extreme cases. There are likely to be some undetected low-mass members in the nucleus, but dynamical evolution will have preferentially evaporated the low mass members (e.g. de la Fuente Marcos 1995).

3.3. ISM

In addition to the group's "poorness", the moderate extinction ($A_V \simeq 0.9^m$) towards the μ Oph group may be one reason why it was previously unnoticed. There are 2 Lynds dark clouds within 3° of μ Oph (#393, #382; Lynds 1962). In the new Catalog of Dark Clouds published by Dobashi et al. (2005), there are 14 clouds and 22 "clumps" within 3° of μ Oph. The low-opacity cloud LDN 393 which covers $\sim$20 square degrees (Lynds 1962) was broken down by Dobashi et al. (2005) into $\sim$25 clumps, with clouds DUKSKUS H189, H159, and H177 accounting for most of the cloud coverage (clouds are from their Table 7). The clumps typically have peak extinctions of $A_V \simeq$ 1-4 mag. They are likely in the foreground of the new cluster, and represent a part of the Aquila Rift cloud complex connecting the Sco-Oph molecular clouds ($\ell \simeq 355°$; $\sim$140 pc; de Zeeuw et al. 1999) with the Serpens clouds ($\ell \simeq 30°$; $\sim$225 pc; Straižys et al. 2003). To estimate how much gas is associated with the dark clouds near μ Oph, I take the integrated extinction-area values from Dobashi et al. (2005) for clouds within 3° (9 pc, projected) of the cluster nucleus, assume a distance of $d \simeq 150$ pc, and adopt the dust-gas ratio from Savage & Mathis (1979). The total gas mass of the dark clouds is then approximately 5000-13000 $M_\odot$.

3.4. Spread in Distances

As stated in §2.3, the *Hipparcos* and Tycho parallaxes for the nine members are statistically consistent with a mean distance of $\simeq$173 pc. However it is not clear whether they are consistent with lying within a range of distances similar to their projected size on the sky (i.e. $\sim$5-10 pc), or the estimated tidal radius (4 pc). Here I estimate a plausible upper limit to the spread in the distances to the individual cluster members, *assuming that the members have identical space motions with negligible velocity dispersion* (physically motivated by the results from §3.2).

A cluster member's distance from the Sun (d_i in pc), angular separation from its group

similar in population to nearby ECs like NGC 2024, Mon R2, and Cha I (Porras et al. 2003).

convergent point (λ_i), proper motion component pointing towards the group's convergent point (μ_{vi} in mas yr^{-1}), and the magnitude of the cluster's space velocity (i.e. V in km s^{-1}), are related through the classic formula (e.g. Atanasijevic 1971):

$$d_i \;=\; \frac{1000\,V\,sin\,\lambda_i}{A\,\mu_{vi}} \tag{4}$$

where A is the astronomical unit in useful units (4.74047 km yr s^{-1}). For cluster members with negligible velocity dispersion and spread in λ, the predicted dispersion in the distances amongst the cluster members (σ_d^{int}) is approximately:

$$\sigma_d^{int} \;\simeq\; \frac{1000\,V\,sin\,\overline{\lambda}}{A\,\overline{\mu_v^2}}\,\sigma_{\mu_v}^{int} \tag{5}$$

where I have defined $\sigma_{\mu_v}^{int}$ as the intrinsic dispersion in μ_v values unaccounted for by observational errors (here presumed to be due to the spread in distances only), and $\overline{\lambda} = 133^{\circ}.9$, $\overline{\mu_v} =$ 23.9 mas yr^{-1}, and $V = 27.2$ km s^{-1} for the cluster sample. The observed 1σ dispersion in μ_v values is $\pm$1.2 mas yr^{-1} (§3.2), and the mean observational error in μ_v is $\pm$1.0 mas yr^{-1}. This leaves an intrinsic scatter of $\sigma_{\mu_v}^{int} \simeq 0.7$ mas yr^{-1} of unaccounted dispersion. If we attribute this spread in the μ_v proper motions solely to the dispersion in distances to the cluster members using equations (4) and (5), then the upper limit on the dispersion in distances is $\sigma_d^{int} \simeq$ 5 pc. If all of the stars were at the same distance, and the intrinsic spread in μ_v values were attributed to a 1D velocity dispersion, then the data would imply a velocity dispersion of 0.6 km s^{-1}. However, a 1D velocity dispersion this large can be ruled out since the spread in μ_τ values (the component perpendicular to μ_v) is negligible compared to the observational errors (§3.2). Based on this analysis, it appears likely that the 1σ dispersion in the distances to the individual cluster members is of order $\pm$5 pc, consistent with the idea that the depth of the group is similar in size to the projected diameter of the group, and similar in magnitude to the estimated tidal radius.

4. Summary

A new, young, nearby candidate stellar aggregate in Ophiuchus is reported. The group consists of the 4th magnitude B8 giant μ Oph and eight co-moving B- and A-type stars in Ophiuchus. The color-magnitude and astrometric data are consistent with the hypothesis that these stars constitute a co-distant (173 pc), co-moving, and coeval (120 $\pm$ 25 Myr) stellar group. The group's one-dimensional velocity dispersion is unresolvable with the best available long baseline proper motion data, consistent with the minuscule value predicted from dynamical considerations ($\sim$0.2 km s^{-1}). Roughly half of the group's observed stellar mass ($\approx$24 $M_\odot$) appears to be concentrated within a nucleus with half-mass radius of $r_h \simeq$ 0.4 pc. A kinematic analysis of the proper motion components pointing towards the group convergent point suggests that the intrinsic scatter in the distances to the individual group members is probably of order $\pm$5 pc, similar in size to the inferred tidal radius (4 pc). If the census of 1.5-5.5 $M_\odot$ members is complete, and the group formed with a normal initial mass function, then the initial population of the new group may have been of order $\sim$200 systems. The space motion and age of the group are similar to that of the Pleiades, α Per cluster, and AB Dor Moving Group, suggesting that these entities may have formed in the same complex some $\sim$10^8 yr ago.

Future observations are clearly desirable to first further test the reality of the group, and secondly to enlarge and better characterize its membership. Analysis of a photometric survey in the nuclear region of the μ Oph cluster is underway (Kenworthy & Mamajek, in prep.) in hopes of identifying the low-mass members, and to further constrain the cluster age via its pre-main sequence. Low-resolution optical spectra will then be used to confirm the youth of the low-mass candidate members. High-resolution spectroscopy will be necessary to measure the radial velocities of all of the candidates in order to further constrain the membership, and independently estimate the velocity dispersion of the group.

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Table 1. Astrometric Data for Candidate Members of μ Oph Cluster

Star Name	Astrometric Alias	$\mu_{\alpha*}$ (mas yr^{-1})	μ_{δ} (mas yr^{-1})	ϖ (mas)	2MASS J
HD 158450	HIP 85618	-14.1 $\pm$ 2.6	-21.2 $\pm$ 1.2	6.04 $\pm$ 2.15	17294397-0801031
HD 158450	TYC 5659-196-1	-13.4 $\pm$ 1.1	-23.9 $\pm$ 1.2	-5.40 $\pm$ 9.80	”
HD 158450	2UCAC 28939300	-13.3 $\pm$ 1.1	-21.6 $\pm$ 1.1	...	”
HD 158450	ASCC 1321674	-12.8 $\pm$ 1.7	-23.7 $\pm$ 1.6	5.51 $\pm$ 2.15	”
HD 158838	TYC 5663-310-1	-10.5 $\pm$ 1.4	-22.1 $\pm$ 1.5	0.50 $\pm$ 6.90	17315378-1027164
HD 158838	2UCAC 28223894	-10.3 $\pm$ 1.2	-21.9 $\pm$ 1.1	...	”
HD 158838	ASCC 1404541	-9.9 $\pm$ 1.9	-21.5 $\pm$ 1.3	0.50 $\pm$ 6.90	”
HD 158875	TYC 5659-186-1	-12.0 $\pm$ 1.3	-19.5 $\pm$ 1.5	13.40 $\pm$ 25.60	17320307-0912018
HD 158875	ASCC 1321733	-11.2 $\pm$ 1.2	-19.5 $\pm$ 2.1	13.40 $\pm$ 25.60	”
HD 158875	2UCAC 28575500	-12.7 $\pm$ 1.0	-21.1 $\pm$ 1.2	...	”
HD 159209	HIP 85936	-9.1 $\pm$ 1.4	-20.7 $\pm$ 0.5	4.58 $\pm$ 1.40	17334689-0755034
HD 159209	TYC 5659-41-1	-11.0 $\pm$ 1.3	-20.8 $\pm$ 1.3	2.60 $\pm$ 11.80	”
HD 159209	2UCAC 29123893	-13.1 $\pm$ 1.1	-21.2 $\pm$ 1.0	...	”
HD 159209	ASCC 1321774	-9.5 $\pm$ 1.6	-21.2 $\pm$ 0.6	4.55 $\pm$ 1.39	”
HD 159874	HIP 86240	-11.5 $\pm$ 1.0	-21.4 $\pm$ 0.6	6.74 $\pm$ 1.05	17372392-0802125
HD 159874	TYC 5660-204-1	-12.0 $\pm$ 1.2	-19.2 $\pm$ 1.2	-3.20 $\pm$ 7.30	”
HD 159874	2UCAC 28940598	-12.5 $\pm$ 1.0	-19.8 $\pm$ 0.9	...	”
HD 159874	ASCC 1321859	-12.0 $\pm$ 1.3	-20.5 $\pm$ 0.9	6.53 $\pm$ 1.04	”
μ Oph	HIP 86284	-11.7 $\pm$ 0.7	-20.4 $\pm$ 0.5	5.94 $\pm$ 0.81	17375071-0807075
μ Oph	TYC 5660-589-1	-11.4 $\pm$ 0.9	-19.1 $\pm$ 0.8	2.60 $\pm$ 3.00	”
μ Oph	ASCC 1321867	-11.3 $\pm$ 1.0	-20.2 $\pm$ 0.8	5.71 $\pm$ 0.81	”
HD 160038	TYC 5660-52-1	-14.7 $\pm$ 1.3	-20.9 $\pm$ 1.3	3.70 $\pm$ 6.60	17380907-0808034
HD 160038	2UCAC 28940731	-13.3 $\pm$ 1.0	-21.0 $\pm$ 1.1	...	”
HD 160038	ASCC 1321875	-13.7 $\pm$ 1.6	-20.6 $\pm$ 1.7	3.70 $\pm$ 6.59	”
HD 160037	HIP 86318	-10.7 $\pm$ 1.2	-20.8 $\pm$ 0.8	6.21 $\pm$ 1.23	17381246-0806212
HD 160037	TYC 5660-255-1	-10.5 $\pm$ 1.1	-20.2 $\pm$ 1.1	-18.90 $\pm$ 11.80	”
HD 160037	2UCAC 28940741	-11.3 $\pm$ 0.9	-20.7 $\pm$ 0.9	...	”
HD 160037	ASCC 1321877	-9.6 $\pm$ 1.0	-20.5 $\pm$ 1.0	5.94 $\pm$ 1.23	”
HD 160142	HIP 86343	-11.7 $\pm$ 1.5	-20.3 $\pm$ 1.0	6.26 $\pm$ 1.66	17383811-0850277
HD 160142	TYC 5660-504-1	-11.6 $\pm$ 1.2	-19.0 $\pm$ 1.2	-4.80 $\pm$ 12.60	”
HD 160142	2UCAC 28756716	-11.0 $\pm$ 0.9	-18.8 $\pm$ 1.0	...	”
HD 160142	ASCC 1321889	-11.4 $\pm$ 1.6	-20.3 $\pm$ 1.4	6.07 $\pm$ 1.65	”

Note. — The astrometric aliases provide the reference for the proper motion and parallax data, which are from the *Hipparcos* and Tycho catalog (Perryman & ESA 1997), Tycho-2 catalog (Høg et al. 2000), 2UCAC catalog (Zacharias et al. 2004), and the ASCC compiled catalog (Kharchenko 2001). For stars with TYC names, the proper motions are from Tycho-2 (Høg et al. 2000) and the parallaxes are from Tycho-1 (Perryman & ESA 1997).

Table 2. Stellar Data for Candidate Members of the μ Oph Cluster

#	Name	Spec. Type	V (mag)	$B-V$ (mag)	$B-V$ Ref.	J (mag)	H (mag)	K_s (mag)	E_{B-V} (mag)	E_{V-J} (mag)	E_{V-H} (mag)	E_{V-K_s} (mag)	R_V	Notes
1	μ Oph	B8 II-IIImnp	4.58	0.12	1,2,3,4,5	4.4:	4.2:	4.2:	0.22	···	···	···	···	(a)
2	HD 159874	B9 IV/V	7.83	0.11	1	7.45	7.42	7.39	0.21	0.47	0.59	0.63	3.3	···
3	HD 160038	B9 V	7.98	0.18	1	7.44	7.40	7.36	0.24	0.60	0.70	0.73	3.5	(b)
4	HD 160037	A0 V	8.90	0.31	1	8.20	8.11	8.08	0.30	0.65	0.77	0.76	3.0	···
5	HD 158838	B9.5 V	8.30	0.16	1	7.72	7.74	7.63	0.19	0.60	0.63	0.69	4.3	···
6	HD 158450	Ap Si(Cr)	8.55	0.37	1,3	7.59	7.54	7.41	0.31	0.90	0.98	0.98	3.9	(c)
7	HD 160142	A0 V	8.99	0.31	1	8.26	8.21	8.13	0.29	0.68	0.76	0.80	3.2	···
8	HD 159209	A0 V	9.00	0.29	1	8.25	8.20	8.10	0.28	0.70	0.78	0.83	3.5	···
9	HD 158875	A(8) (p Si)	10.16	0.51	1	8.65	8.34	8.21	0.28	1.16	1.34	1.39	6.1	(d)
mean	···	···	···	···	···	···	···	···	0.26	0.65	0.74	0.77	3.5	(e)
s.e.m.	···	···	···	···	···	···	···	···	0.02	0.05	0.05	0.04	0.2	(e)
st.dev.	···	···	···	···	···	···	···	···	0.05	0.13	0.13	0.11	0.5	(e)

Note. — All spectral types are from Houk & Swift (1999), V magnitudes are from Perryman & ESA (1997), and JHK photometry is from 2MASS (Cutri et al. 2003). Reference numbers for the best estimate of the $B-V$ color are: (1) Perryman & ESA (1997), (2) Johnson et al. (1966), (3) Hauck & Mermilliod (1998), where $b-y$, $m1$, and $c1$ colors were converted to Johnson $B-V$ via Turner (1990), (4) Cousins (1964), (5) Crawford (1963). The uncertainties in the R_V values for each star are ≈0.2. The last three rows are the unweighted mean, standard error of the mean, and standard deviation for the sample.

[a]The 2MASS photometry for μ Oph is very poor (∼0.2-0.3 mag errors per band), so I do not use this data to constrain the near-IR color excesses or R_V.

[b]*ROSAT* FSC X-ray source (1RXS 173809.5-080749; Voges et al. 2000) with flux rate of 1.80e-2 ct s^{-1}. At distance of 173 pc this translates to an X-ray luminosity of $\log(L_X/\mathrm{erg\,s^{-1}}) = 29.8$ and fractional X-ray/bolometric luminosity ratio of $\log L_X/L_{bol} = –5.4$. The X-ray flux is probably from an active low-mass companion, as the X-ray luminosity is very similar to that of low-mass stars seen in other ∼100 Myr groups (e.g. Pleiades; Stauffer et al. 1994).

[c]HD 158450 is a 0".4 separation binary with a faint companion ($\Delta V = 2.0$; Worley & Douglass 1996). For the reddening calculations, I assumed photospheric colors appropriate for an A0 star (Grenier et al. 1999).

[d]HD 158875 is a 0".9 separation binary with a faint companion ($\Delta V = 3.0$; Worley & Douglass 1996).

[e]HD 158875 is omitted from inclusion in calculating the mean, standard error, and standard deviation of R_V (see §2.2).

Table 3. Properties of the μ Oph Cluster (Mamajek 2)

Property	Quantity
Lucida	μ Oph ($V = 4.58^m$, B8II-IIImnp)
Nucleus Center (J2000)	17^h38^m –8° 06' (§2)
Nucleus Center (Galactic)	17°.0, +12°.3 (§2)
Angular Diam. of Nucleus	20' (§2)
Physical Diam. of Nucleus	1 pc (§2,§2.3)
Parallax ($\overline{\varpi}$)	5.77 ± 0.48 mas (§2.3)
Distance ($\overline{D}$)	173^{+16}_{-13} pc (§2.3)
$\overline{(m-M)_o}$	$6.19^{+0.17}_{-0.19}$ mag (§2.3)
$\overline{\mu_{\alpha*}}$	-12.1 ± 0.4 mas yr^{-1} (§2.5)
$\overline{\mu_{\delta}}$	-20.6 ± 0.4 mas yr^{-1} (§2.5)
$\overline{v_{rad}}$	-18.9 ± 1.3 km s^{-1} (§2.5)
Barycentric Vel. (U, V, W)	(–12, –24, –4) $\pm$ (1, 1, 1) km s^{-1} (§2.5)
$\overline{E_{B-V}}$	0.26 ± 0.02 mag (§2.2)
$\overline{R_V}$ $(= A_V/E_{B-V})$	3.5 ± 0.2 (§2.2)
Mass of Candidate Members	24 $M_{\odot}$ (§3.2)
Half-Mass Radius (r_h)	0.4 pc (§3.2)
Tidal Radius (r_t)	4 pc (§3.2)
Age	120 ± 25 Myr (§2.4)
Absolute Magnitude (M_V)	-2.5^m

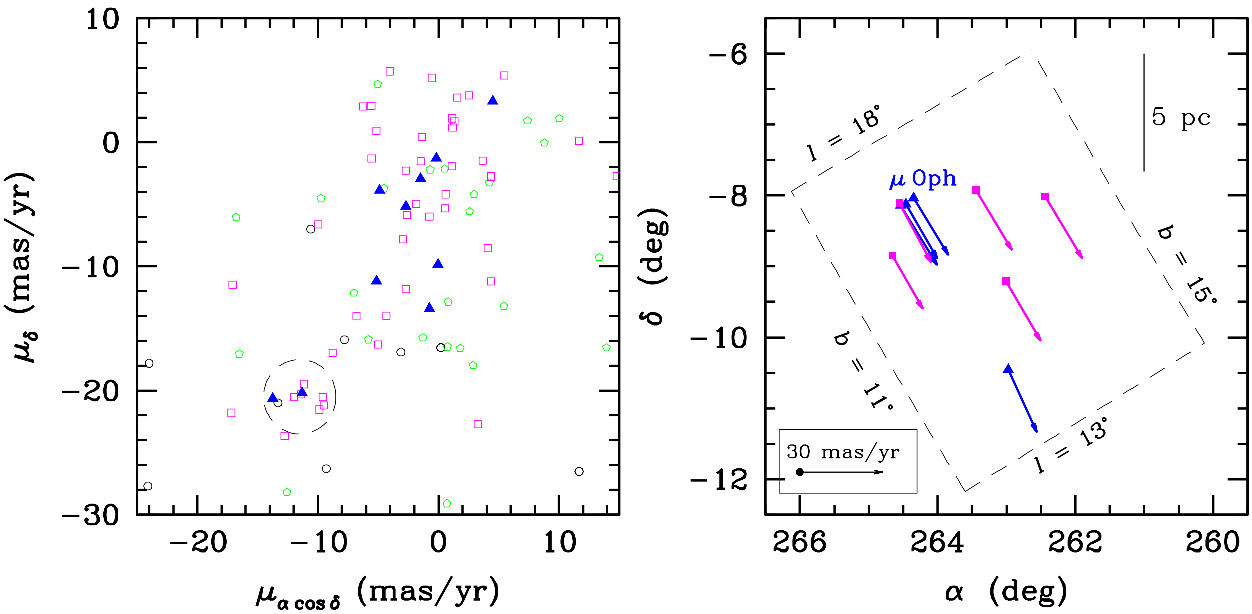

Fig. 1.— Proper motions of stars in the vicinity of μ Oph. Colored points are stars from the ASCC-2.5 catalog, representing stars of spectral type B (*filled blue triangles*), A (*open magenta squares*), and F (*open green pentagons*). Only ASCC stars with measured parallaxes, *BV* magnitudes, and spectral types are plotted. X-ray stars from the *ROSAT* All Sky Survey with counterparts in the UCAC2 and Tycho-2 catalogs are shown as *open black circles*. Some ASCC stars appear twice (i.e. they are RASS X-ray sources). HD 160038 (B9V) is the only X-ray source selected. The *left plot* shows the proper motions for ASCC and RASS stars over the entire 7° × 7° region centered on (α, δ) = (263°.8, –9°.0). The *right plot* shows the positions and proper motion vectors for stars with proper motions encircled in the left plot (within 3 mas yr^{-1} of $\mu_{\alpha*}$, μ_δ = –11.5, –20.5 mas yr^{-1}). The *dashed lines* show Galactic latitude and longitude lines which encompass the group. The 5 pc segment is for the adopted distance (173 pc; §2.3).

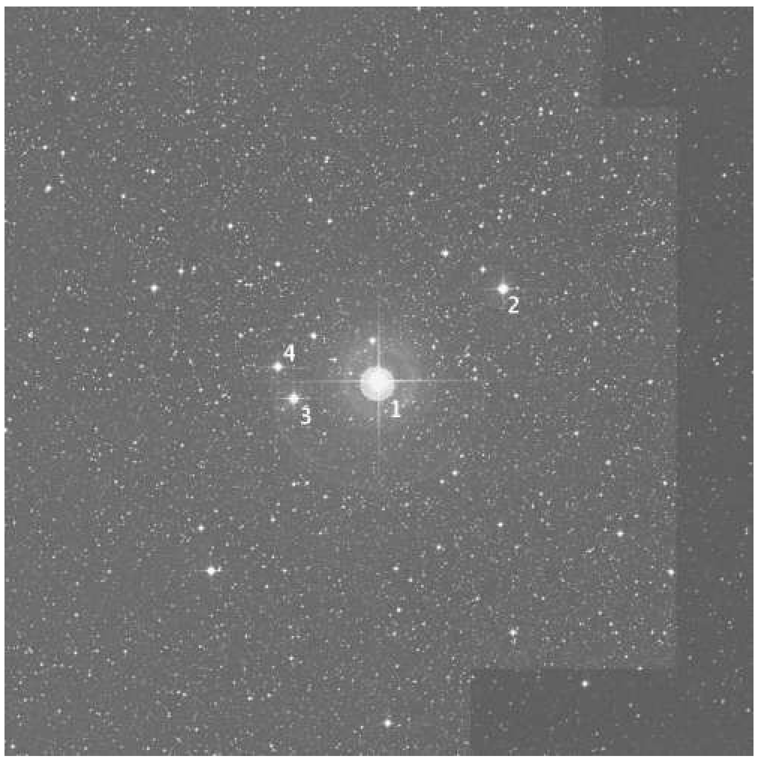

Fig. 2.— Second generation Digitized Sky Survey (red) image centered on μ Oph. Field of view is 40' (2.0 pc at $d = 173$ pc). Stars are indexed in Table 2, where #1 is μ Oph itself.

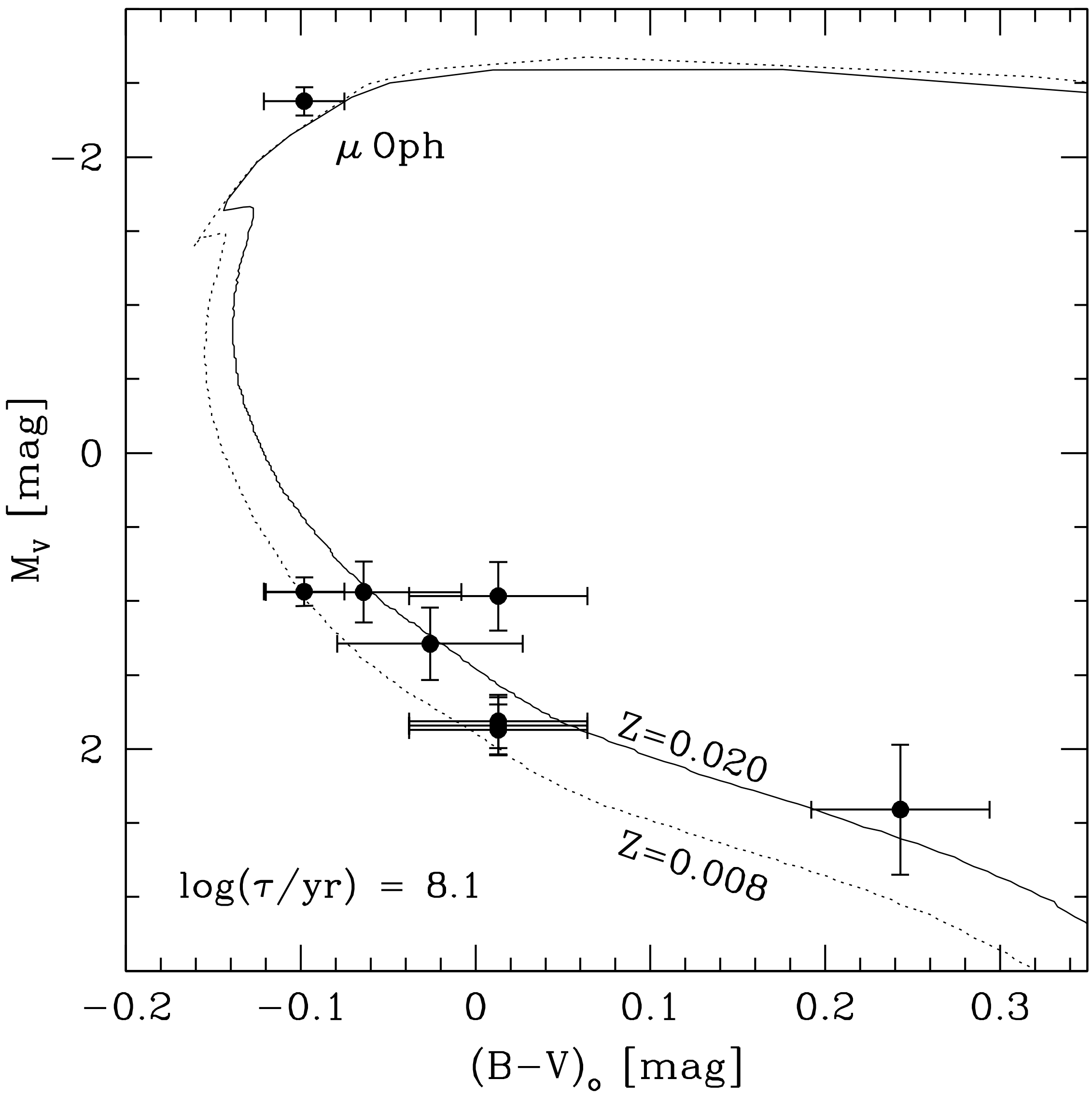

Fig. 3.— Dereddened color-magnitude diagram for μ Oph candidate members selected via proper motions from Fig. 1, and using photometry from Table 2. The errors in $(B-V)_0$ reflect spectral type uncertainties of ±1 subtype, whereas the errors in M_V include errors in the color excess and R_V (but not distance, which could introduce a systematic shift of ±0.18 mag in M_V). Two isochrones are shown for log(age/yr) = 8.1, for two metal mass fractions which bracket the solar metallicity ($Z \simeq 0.015$). The isochronal age of μ Oph is nearly independent of metallicity, and leads to a post-MS age estimate of 120 ± 25 Myr (§2.4).